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ABSTRACT

We present a new implementation of the NNLO QCD corrections to three-jet final states and related event-shape observables in electron–positron annihilation. Our implementation is based on the antenna subtraction method, and is performed in the NNLOJET framework. The calculation improves upon earlier results by taking into account the full kinematical information on the initial state momenta, thereby allowing the event orientation to be computed to NNLO accuracy. We find the event-orientation distributions at LEP and SLC to be very robust under higher order QCD corrections.

The production of hadronic final states in electron–positron annihilation at high energies offers a unique laboratory for testing the theory of the strong interaction, quantum chromodynamics (QCD). Experiments at LEP and SLD have collected a wealth of precision data on jet cross sections and event-shape distributions [1–5]. Precision studies of these data included establishing the gauge group structure of QCD, measurements of the strong coupling constant and investigations of the all-order structure of large logarithmic effects in QCD [6]. These studies rely on the comparison between the data and theory predictions, with the inherent uncertainty of the theoretical calculations due to truncating a perturbative expansion often being a limiting factor. Most of the original LEP and SLD studies were based on the then available NLO theory predictions for event shapes and cross sections [7–9]. These calculations are in the form of fixed order parton-level codes, which produce weighted events containing sets of parton momenta and which can adapt in a flexible manner to the jet definition and event-shape variables used in the experimental studies.

The calculation of NNLO corrections to three-jet production and related event-shape observables [10,11] enabled these data to be confronted with increasingly precise predictions, and led to a variety of new precision QCD studies [12]. The calculation of jet-like observables at NNLO requires a method for the cancellation of infrared singular contributions across channels of different partonic multiplicity. Both early calculations [10,11] (with the EERAD3 code of [10] documented in detail in its public release [13]) were based on the antenna subtraction method [14]. They have been recently complemented by a new calculation [15] based on the colourful-subtraction method [16].

To apply the antenna subtraction method to a broad number of processes, we are currently developing the NNLOJET code, which is a fixed order parton-level code that provides the framework for the implementation of jet production to NNLO accuracy. Besides containing the necessary event generation infrastructure (phase-space integration, event handling and analysis routines), it supplies the unintegrated and integrated antenna functions and the phase-space mappings relevant to all kinematical situations. The multi-dimensional phase space integration is performed using the adaptive Monte Carlo integrator VEGAS [17]. Processes included in NNLOJET up to now are Z and Z+jet production [18], H and H+jet production [19] as well as single-inclusive and di-jet production in hadron–hadron collisions [20] and in deep inelastic scattering [21].

Our new implementation of the NNLO QCD corrections to $e^+e^- \to 3j$ is performed in the NNLOJET framework. The relevant matrix elements correspond to different kinematical crossings of the ones already used [22–24] in the $Z + j$ and deeply inelastic jet production processes. The structure of the antenna subtraction terms for these matrix elements is documented in detail in [25]. We validated the new implementation against EERAD3 [13] for the canonical set of LEP event shapes and jet cross sections. While the EERAD3 implementation [13] was based on the matrix elements for virtual photon decay $\gamma^* \to q\bar{q}g$ (and higher order corrections to it), NNLOJET now contains the full $e^+e^- \to q\bar{q}g$ matrix elements through to NNLO in massless QCD. It therefore allows to properly account for the correlation between the final-state parton directions and the incoming electron and positron beams.

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Most of the LEP and SLC measurements of event shapes and jet cross sections [1–5] were corrected to a full 4π acceptance. They do not depend on the angular correlation between the final state hadrons and the incoming electron–positron direction. Measurements of fiducial cross sections (restricted to the actual acceptance of the detector) are typically not available, the only exceptions being a few studies of oriented event-shape distributions [26,27], which are measured in fixed intervals in the angle between the event's thrust axis and the incoming beam direction. An indication of the quality of the extrapolation to full 4π acceptance can however be gained from studying event-orientation variables, which describe the full angular correlation between the hadronic final state and the incoming beams.

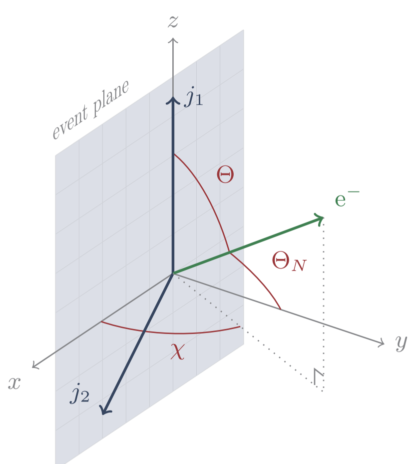

Fig. 1. Definition of the three Euler angles characterising the event orientation. j_1 denotes the highest-energy jet, j_2 the sub-leading jet [32].

Three-particle (or three-jet) production in the e^+e^- centre-of-momentum frame always results in a final state with momenta in a plane, due to momentum conservation. The orientation of this event plane with respect to the initial state is described by three Euler angles: (Θ, Θ_N, χ) [28]. Taking the event plane in (x, z) and using the highest-energy final state object to define the z-axis, the incoming electron direction is defined through the polar angle Θ and the azimuthal angle χ. The third angle Θ_N is then formed by the electron direction and the event plane normal. The choice of coordinate system and the definition of the angles is displayed in Fig. 1, reproduced from [32].

For three-jet final states, event orientation distributions were measured initially by TASSO [29] and subsequently by DELPHI [30], L3 [31], and SLD [32]. In all measurements, the JADE algorithm was used to identify the final-state jets, and one-dimensional distributions in Θ, Θ_N or χ were measured. These measurements were compared with the leading-order, leading-logarithmic multi-purpose event generator simulations HERWIG [33] and JETSET/PYTHIA [34], which all provided a very good description of the data. This observation motivates the use of these simulation programs to extrapolate the canonical event shape and jet cross sections measurements to full 4π acceptance.

For this procedure to be reliable, it is however vital that the shapes of the leading order event-orientation distributions are not distorted by higher-order QCD corrections. Surprisingly enough, this issue has never been investigated in a systematic manner. By using an approximation to the real-radiation contributions, NLO QCD corrections to event orientation were estimated to be small in [35]. Comparing the JETSET predictions with exact real-radiation matrix elements and parton-shower approximation, SLD [32] at-

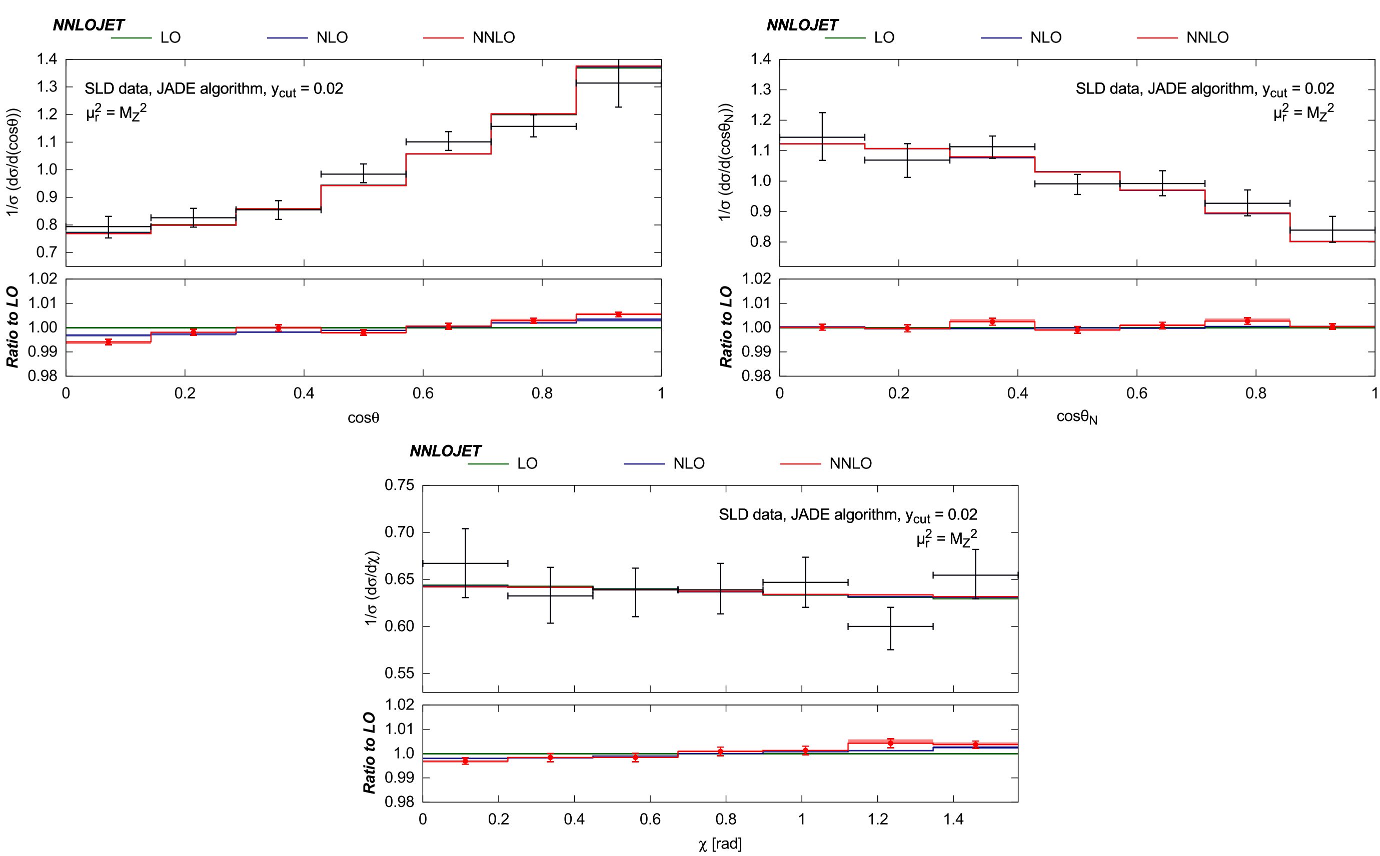

Fig. 2. Event orientation distributions for three-jet events (JADE algorithm, $y_{cut} = 0.02$), compared to SLD data [32].

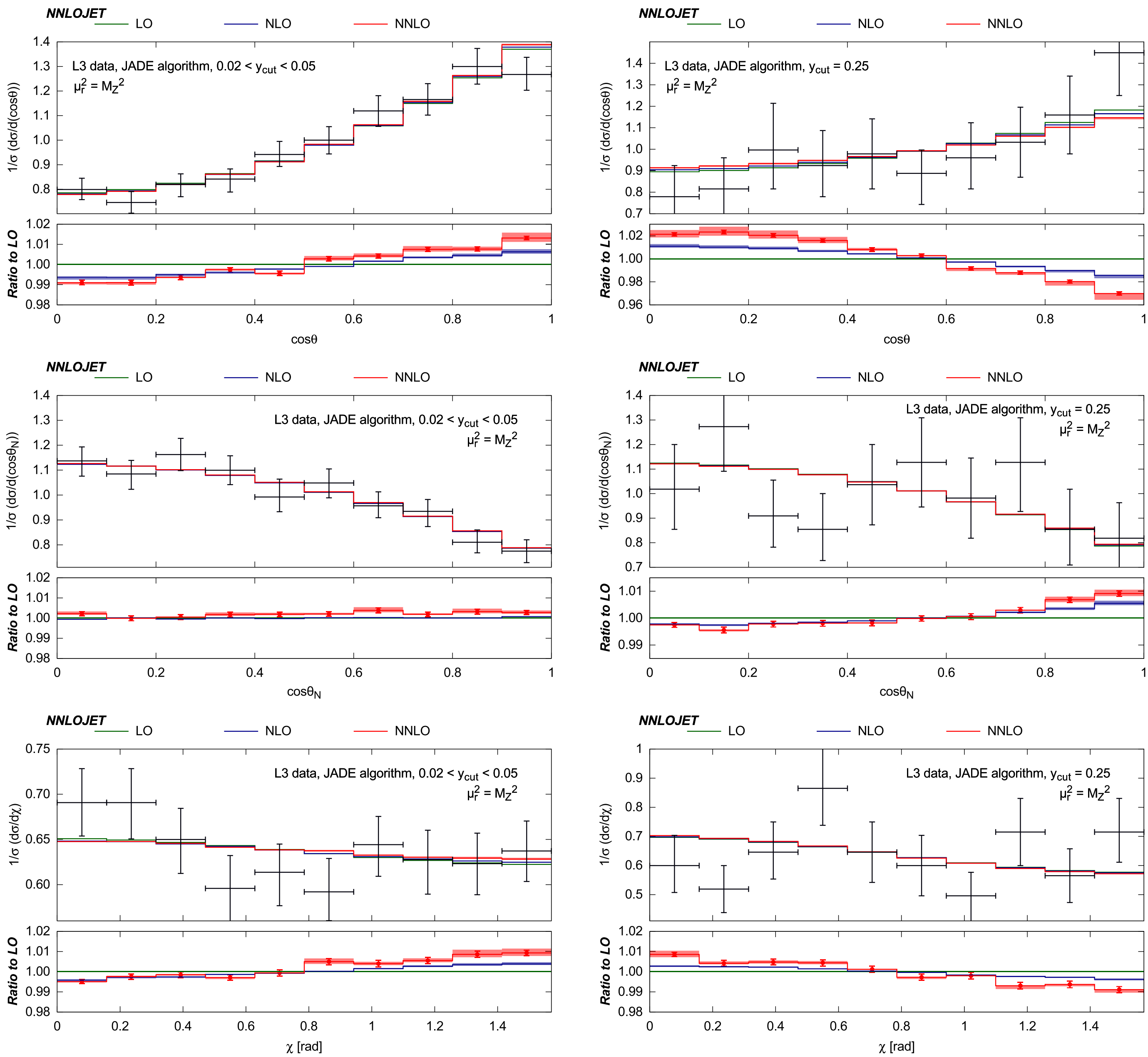

Fig. 3. Event orientation distributions for three-jet events (JADE algorithm) compared to L3 data [31]. Left: $0.02 \le y_{\rm cut} \le 0.05$, right: $y_{\rm cut} = 0.25$.

tempted to quantify the potential magnitude of real-radiation effects at NLO, which were found to be of limited impact.

With the NNLOJET implementation of jet production in e^+e^- annihilation, we are now able to compute the NLO and NNLO corrections to the event orientation distributions. We consider the kinematical situations that were investigated by L3 [31] and SLD [32], which provide more precise measurements than in the earlier studies. Both experiments perform their measurements on an exclusive three-jet sample. The jets are identified using the JADE algorithm [36], with a range of jet resolution parameters $y_{\rm cut}$ for L3, and for fixed $y_{\rm cut} = 0.02$ for SLD. The distributions in (Θ, Θ_N, χ) are normalised to the three-jet cross section, such that they all integrate to unity by construction. Besides cancelling potential sources of systematic uncertainty, this normalisation condition makes the theoretical predictions at leading order independent of α_s. Consequently, the variation of the renormalisation scale will not necessarily be a good quantifier for the potential impact of higher order corrections, and one should rather look order-by-order into the relative size of the corrections.

The experimental data have all been corrected to 4π acceptance, with SLD [32] also providing the uncorrected data. By comparison, it can be seen that the corrections affect the event orientation distributions only for $\cos(\Theta) \gtrsim 0.7$, $\cos(\Theta_N) \lesssim 0.3$, $\chi \lesssim \pi/4$. These can be identified from Fig. 1 as the regions where the event plane comes close to the beam direction, such that the final state particles can be partly outside the detector coverage.

Fig. 2 displays the event orientation distributions at LO, NLO, and NNLO for exclusive three-jet events and compares them to the SLD data [32]. The error bands on the NLO and NNLO predictions are obtained by varying the renormalisation scale in the strong coupling constant within a factor [1/2; 2] around the central scale $\mu_R = M_Z$. We also indicate the numerical integration error on the

NNLO coefficients by a red error bar in the ratio plot. We observe that the perturbative corrections modify the leading-order shape of the distributions only at the level of four per mille at NLO and at most one per cent at NNLO. The corrections are most pronounced in $\cos(\Theta)$, where they modify the slope of the distribution, and are even smaller in χ and $\cos(\Theta_N)$.

The L3 experiment measured the event orientation distributions for two ranges in exclusive three-jet events (using the JADE algorithm). Results are given for two jet resolutions: $0.02 \le y_{\mathrm{cut}} \le 0.05$ (fine jet resolution) and $y_{\mathrm{cut}} = 0.25$ (coarse jet resolution). The application of a range in y_{cut} instead of a fixed value is uncommon and requires further explanation: events are classified as three-jet final states if and only if they yield a three-jet final state for all values of y_{cut} in the interval. Since the JADE algorithm yields a monotonous increase in jet multiplicity with decreasing resolution parameter, it is sufficient to find a three-jet final state for both the upper and lower edge of the y_{cut} interval. The event orientation distributions for both values of jet resolution parameters at LO, NLO, and NNLO (with error bands and bars defined as above for SLD) are shown in Fig. 3, where they are compared to data from L3 [31]. For the fine jet resolution, we observe a pattern that is very similar to what we saw for SLD, with corrections at the level of at most one per cent throughout. For the coarse jet resolution, we observe that the corrections to the $\cos(\Theta)$ distribution increase to a maximum of three per cent at NNLO, and that the slope of the corrections to the $\cos(\Theta)$ and χ distributions is inverted compared to the fine jet resolution.

For all distributions, we observe that the scale variation bands at NLO and NNLO do not overlap and that their size increases from NLO to NNLO. Given that the distributions are normalised such that they become independent of α_s at leading-order, scale variation should not be considered a good indicator of residual theoretical uncertainty from missing higher orders for these particular observables. The small absolute magnitude of the corrections both at NLO and NNLO is however a strong indicator for the perturbative stability of the event orientation distributions. It is worth pointing out that the event orientation distributions are normalised to the three-jet cross section, which itself receives sizeable NLO and NNLO corrections [10,11]: the observed smallness of the corrections to the normalised distributions indicates that the NLO and NNLO corrections are substantial in absolute terms, but uniform in the event orientation variables. Consequently, further corrections from quark mass effects (which are known to be small compared to the massless NLO and NNLO terms, [37]) will not modify our findings on the event orientation distributions.

In summary, we presented a new implementation of the NNLO QCD corrections to $e^+e^- \to 3$jet and related event-shape observables, using the antenna subtraction method for the cancellation of infrared singularities between real-radiation and virtual contributions. Our implementation is in the form of the fixed order parton-level code NNLOJET, which can compute infrared-safe quantities using the jet definition and event selection criteria as used in the experimental measurements. Compared to previous implementations, we retain the full dependence on the initial-state lepton kinematics, which allows us to compute fiducial cross sections and event orientation distributions. The latter are particularly relevant in view of precision measurements of event shapes and cross sections at LEP and SLD. In these experiments, results were typically extrapolated from the actual measurements done with restricted detector acceptance to full 4π acceptance, using leading order multi-purpose event simulation programs. By computing the NLO and NNLO corrections to the event-orientation distributions, we can now quantify the impact of higher order QCD effects on these extrapolations. We find that the event orientation distributions are extremely robust under QCD corrections. For a fine jet resolution (where the bulk of precision QCD studies is performed), the corrections up to NNLO modify the distributions up to at most one per cent. By going to a more coarse jet resolution, the magnitude of the corrections increases slightly to three per cent, and the slopes of the corrections in some of the distributions are inverted. Our findings support the validity of the acceptance correction procedure applied in precision QCD studies at LEP and SLD. When aiming for per-mille level precision in QCD measurements at a future Z factory, these corrections will become of relevance, and it should be considered to concentrate on measurements and interpretation of fiducial cross sections instead of extrapolating to full acceptance.

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